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USING THE BOREHOLE JACK TO DETERMINE CHANGES IN RIVER ICE STRENGTH

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INTRODUCTION

Ice strength plays a critical role in the initiation and progression of river-ice breakup and partially determines the stress imparted to structures during subsequent ice runs. In general, breakup occurs when downstream forces exceed the resistance operating to keep the ice sheet in place and intact. During melt periods, rising stage and velocity produce an increase in the downstream forces but the resistance can also decrease, particularily when the ice cover detaches from support zones, such as banks and shoals, or when the strength of the ice sheet decreases. Changes in strength result from overall warming of the cover and from radiation melt within the ice sheet. An ability to measure such changes could greatly assist in the prediction of the timing and severity of breakup.

Because of the weakness of the ice during the pre-breakup period, strength measurements must be carried out *in situ*. Past experiments have relied on penetration, small-scale compression, and simply-supported and cantilever beam tests. This paper reports on the use of a borehole jack during an 18-day period immediately preceding breakup. The results are related to detailed radiation balance measurements conducted over the same period and to calculated changes in internal ice porosity.

BACKGROUND THEORY

Radiation Balance

Radiative warming and the transfers of sensible and latent heat by convection and conduction are all important to the thermal ripening and thinning of the ice cover. It is solar radiation, however, which can also produce significant decreases in the internal strength of the ice. Upon reaching the surface, short-wave radiation is either reflected, consumed in melt, or penetrates into the underlying ice where it is rapidly attenuated, depending on grain size, shape and orientation.

Short-wave radiation reaching the cover surface (S_0, W/m^2) is expressed as

$$[1] \qquad S_0 = S_i(1 - \alpha)$$

where S_i is the total direct and diffuse incoming short-wave radiation (W/m^2) and α is the albedo. The attenuation of radiation is commonly defined by the relation:

$$[2] \qquad S_x = S_0 e^{-\upsilon x}$$

where S_x is the radiation (W/m^2) reaching depth x (m) and υ is the extinction coefficient. Attenuation, however, is also known to be spectrally selective. Based on measurements obtained for first year blue sea ice by Grenfell and Maykut (1977), Ashton (1985) derived the following equation using a power law dependence of υ on x:

$$[3] \qquad S_x = S_0 e^{-1.36x^{0.5}}$$

If radiation attenuated within the ice sheet is absorbed at a higher rate than heat can be conducted away to colder parts of the ice, or to the ice-water and ice-air boundaries, melt will occur. This usually occurs at the grain boundaries, thereby increasing the ice porosity and eventually leading to the commonly-observed phenomena termed "candling", in which individual crystals are separated, creating long, candle-like forms.

Borehole Jack

The borehole jack has been primarily used as a field-portable method for determining *in situ* mechanical properties of first- and multi-year sea ice in the offshore regions of Canada's Arctic coast. Here, exploration for oil and gas, from ice island platforms and man-made structures, necessitates an understanding of ice strength and load bearing capacity. Similarily, for river-ice concerns such as on-ice travel and breakup prediction, knowledge of the mechanical properties of river ice is

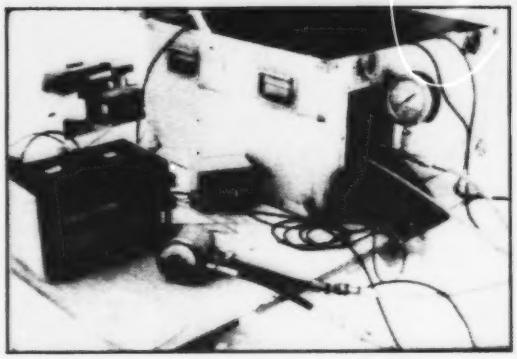

Fig.1. Borehole jack test equipment.

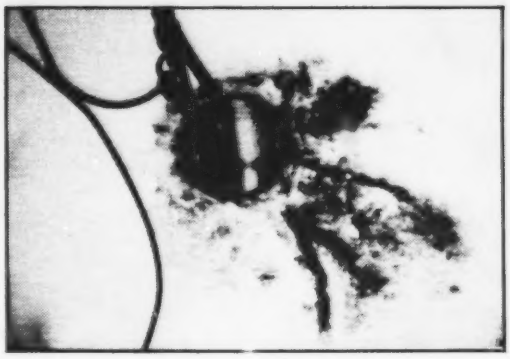

Fig.2. Borehole jack being inserted in a 150 mm diameter test hole cored vertically from the ice sheet.

required to understand the mechanisms of decay and fracture/failure processes.

The borehole jack (Fig.1) consists of a hydraulic cylinder which, when pressurized, pushes indentor platens into the walls of a borehole cored in the ice sheet (Fig.2). The pressure required to indent the platen into the ice is representative of the overall ice strength in compression. The deforming ice volume, however, surrounding the platen-ice interface exhibits several distinct zones produced by various combinations of compressive, shear and tensile forces under the action of platen indenture. These zones, as described by Masterson (1983), are: i) adfrozen crushed bulb, ii) hemispherical crushed, iii) radially cracked, and iv) elastic, each exhibiting unique material properties. In modelling jack behaviour, in order to derive elastic and load bearing properties from jack tests in ice, Masterson (1983) considered the adfrozen crushed zone to be part of the infinitely stiff indentor and conducted his analysis by examining the expansion of a spherical hole in an infinite elastic-plastic-brittle medium. The details of this model are beyond the scope of this paper, however it should be noted that the test results reported herein are used as an "index" of ice strength for

the purposes of this river-ice study. Interested readers are referred to work by Sinha (1987) where, in an attempt to make borehole jack data quantitatively useful, experiments were conducted to relate the results from jack tests to those from uniaxial (confined/unconfined) compression tests.

Ice failure processes

River ice-breakup is initiated and progresses by a variety of fracturing and fragmenting processes, including vertical and horizontal bending and crushing, the relative importance of each depending on such parameters as ice sheet thickness, rate of loading and ice strength. The effect of a borehole jack test is most representative of ice failure in compression.

STUDY SITE

Location

The study was carried out in the Spring of 1987 on the Liard River near its confluence with the Mackenzie River (61°53'N, 121°22'W). The Liard River drains 277,000 km^2 and has a mean annual discharge of 2,580 m^3/s (Environment Canada 1980). On average, mean daily air temperature rises above freezing on April 19 and climbs to 7°C by May 7 (Environment Canada, unpublished). Breakup of the Liard River near its mouth occurs in early May with the first deterioration of the snow and ice cover beginning in late April. Details of the process of ice decay and clearance at this site can be found in Prowse (1984, 1986). Ice conditions in 1987 primarily consisted of a surface dominated by a rough freeze-up cover (herein referred to as white ice) interspersed with localised zones of columnar black ice (Fig.3), all covered at the beginning of the experiment by 0.45 m of snow.

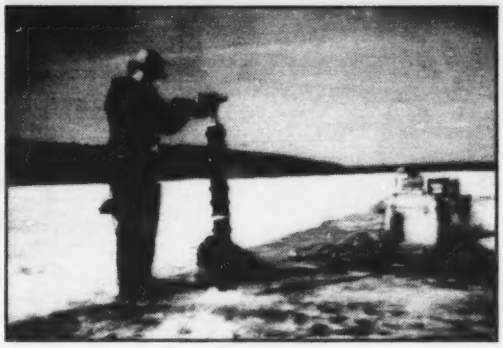

Fig.3. Coring on black ice strip

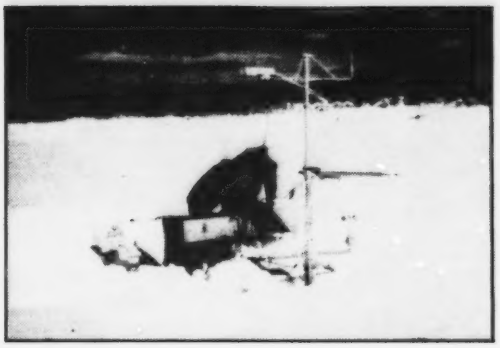

Fig.4. Energy balance equipment

Equipment and Methodology

Incoming and outgoing short-wave radiation were measured with a Swissteco two-component pyranometer and ice temperatures with Fenwal UUT-51J1 thermistors placed at 0.1-m intervals through the ice sheet. All energy balance data were recorded on Campbell Scientific Ltd. CR21 microloggers with a 10 second sampling rate (Fig.4). A 20-point grid was established to monitor changes in snow depth and density.

The test area for the borehole jack was 50 m upstream from the energy balance equipment. Sites, separated by a minimum of 15 m and arranged in a grid pattern, were used for a daily series of 5 to 10 measurements. Eight series of tests were conducted over the twenty-day period. For each test, the jack was placed at the mid-point of the ice thickness (1.0 m for white ice and 0.65 m for black ice). During indenture, applied hydraulic pressure and platen displacement were recorded on a strip-chart recorder.

FIELD RESULTS

During the study period, surface conditions changed from a deep blanket of snow (0.45 m on April 11; Fig.5) to expanses of white ice and localised zones of ponded meltwater on April 24. With snow cover depletion, the albedo decreased from 0.85 on April 11 to a nearly constant value

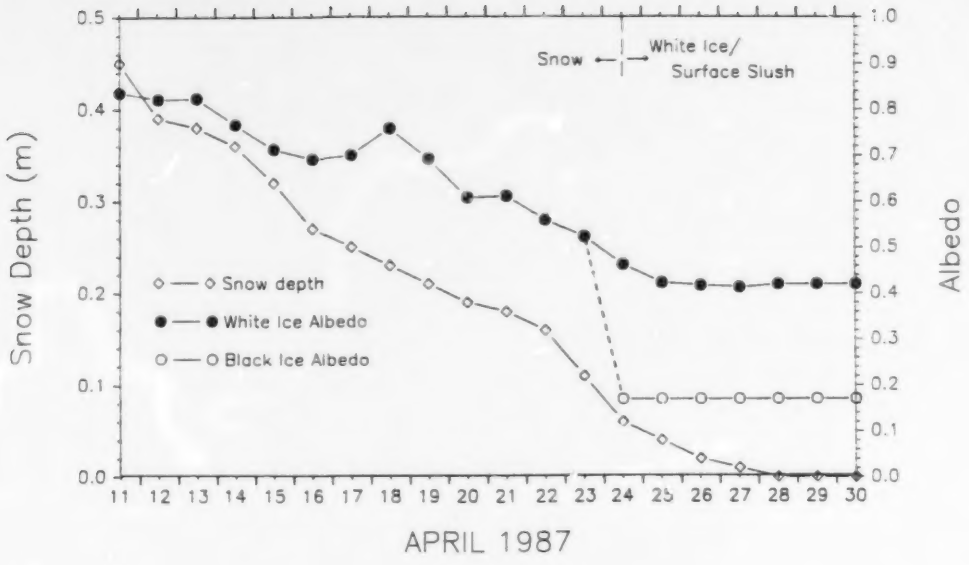

Fig.5. Changes in snow depth and surface albedo.

of 0.42 between April 24 and the end of the study period (Fig.5). This latter value represents the albedo of the white ice that became exposed after the removal of the snow cover. Some zones of columnar black ice also became exposed with the depletion of surface snow and, although no direct radiation measurements were conducted over these zones in 1987, Prowse (1987) measured an albedo of 0.17 for black ice in a similiar state of decay at this same location in 1984. This value has been employed in subsequent calculations.

Prevailing meteorologic conditions and the results of detailed energy balance (see Prowse *et al.* 1988) are shown in Fig.6. Daily heat flux to the ice cover (white ice) ranged from near zero to approximately 12 $MJ/m^2/d$ over the study period. Separate results are shown for the white ice and black ice covers for the period April 24-30. Prowse *et al.* (1988) noted that surface melt during this period was primarily driven by the radiation components although sensible heat dominated on a few days.

ANALYSIS

Radiation absorption

Calculation of radiation received at the surface (ice or snow), S_0, is straightforward using [1] with values for α and S_i shown in Figs 5 and 6. Subsequent calculation of radiation absorption within the ice sheet over the period April 24-30 can then be made by using S_0 in [3] and integrating over the entire ice thickness: 1.0 m for the white-ice and

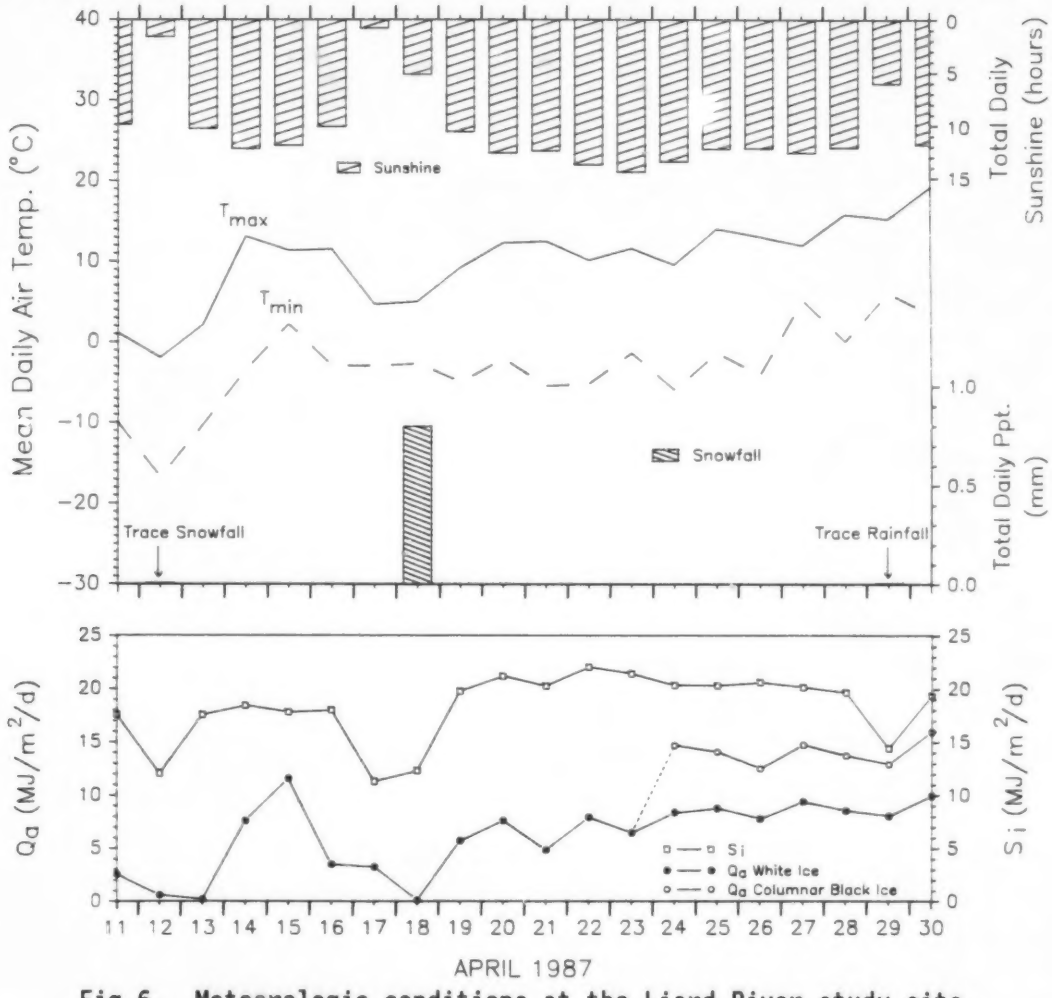

Fig.6. Meteorologic conditions at the Liard River study site.

0.65 m for the black-ice strips. During the period of snow cover however, radiation losses due to attenuation within the snow also had to be

considered. This was accomplished using [2] with the snow depths in Fig.5 and an appropriate value of υ for snow. In reviewing the relevant literature, Prowse and Stephenson (1986) found bulk extinction coefficients for snow to range from near 10 for snow in a melting state, to 25 for dry compact snow, and to near 40 for newly fallen, light density snow. In view of the melt conditions prevailing during the study period, υ was set to 10 and [2] used to calculate the amount of radiation reaching the bottom of the snow cover. This value of S_x was then used as S_o in [3] and integrated for the total ice thickness.

Strength tests

Applied stress (σ_1, MPa) versus platen displacement (δ, mm) curves for two of the eight series of jack tests are presented in Figs 7 and 8. The curves in Fig.7 depict initial tests conducted just prior to the ice sheet attaining a 0°C isothermal state (April 12). These tests provide a reference level of strength from which further comparisons are made. From this point forward, radiative melt throughout the depth is the major contributor to structural ice decay. The curves in Fig.8 depict tests conducted during the later stages of the study period (April 26); the ice having accumulated significant quantities of heat from short-wave radiation.

The curves of Figs 7 and 8 emulate the basic "stress-strain" material-property curve of more common engineering materials. In Fig.7, the applied stress rapidly rises to a peak then decreases to a post-peak level as displacement continues. In contrast, the curves of Fig.8 gradually rise to an ultimate value and never exhibit a well-defined peak or yield point. In both cases, as is characteristic of any borehole jack test, the initial portion of the stress-displacement curve is non-linear. This is due in part to borehole wall roughness and assembly bolt holes of the platen surface acting as stress raisers and causing immediate localized failure at the platen-ice interface. In general, the peak or yield points obtained from the tests can only be considered as indices of "strength" because of the complex manner in which the jack interacts with the surrounding ice matrix.

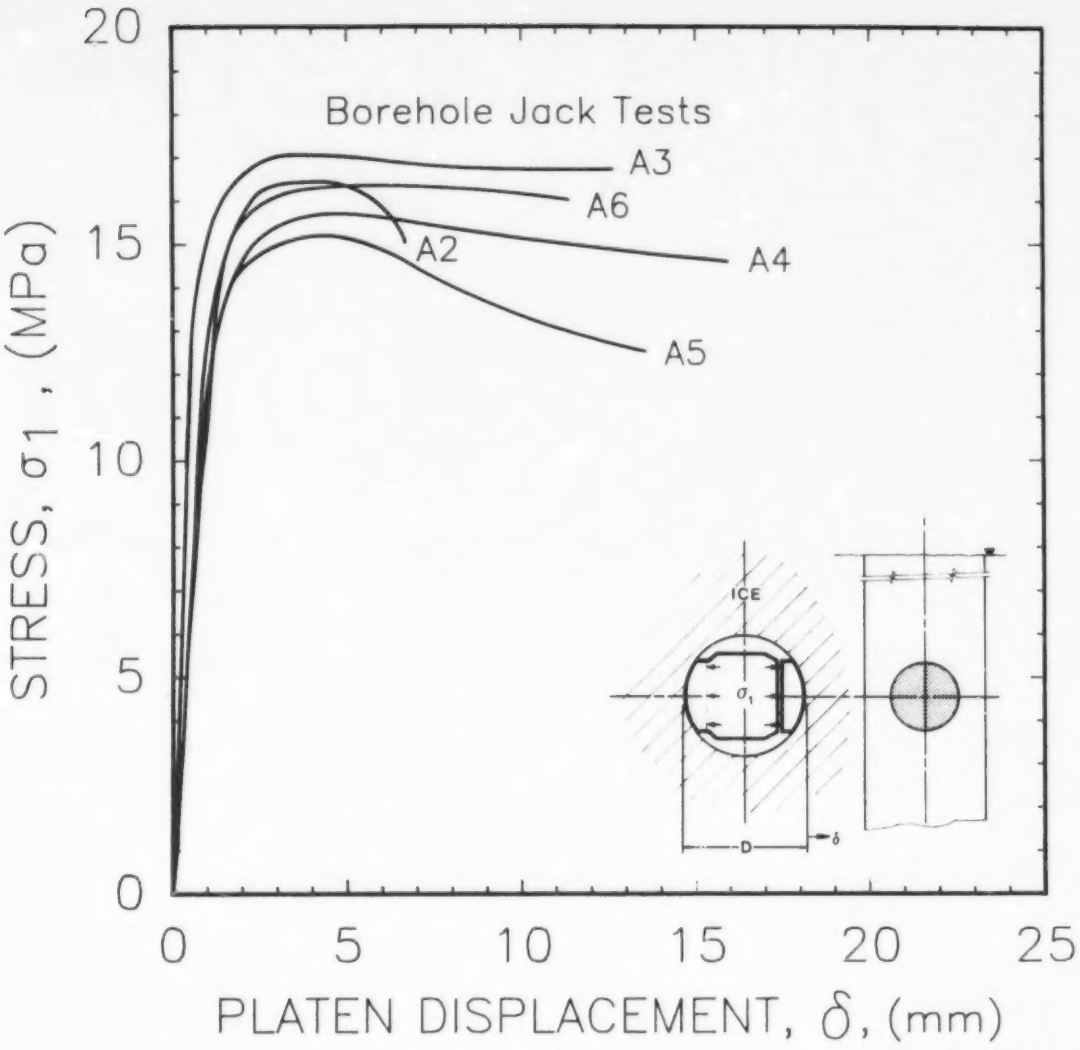

Fig.7. Typical applied stress-platen displacement curves for initial test series (A) conducted April 12.

Any measure of ice strength is known to vary with strain rate. Although the characteristics of the test system used in this study did not allow control of indenture rate, data indicate a nominal strain rate, at the platen-ice interface, of approximately 10^{-3} s^{-1} for a majority of the tests.

Two criteria were employed to define a strength value. Firstly, the ultimate value of applied stress, σ_{1u} (or ultimate platen pressure), was

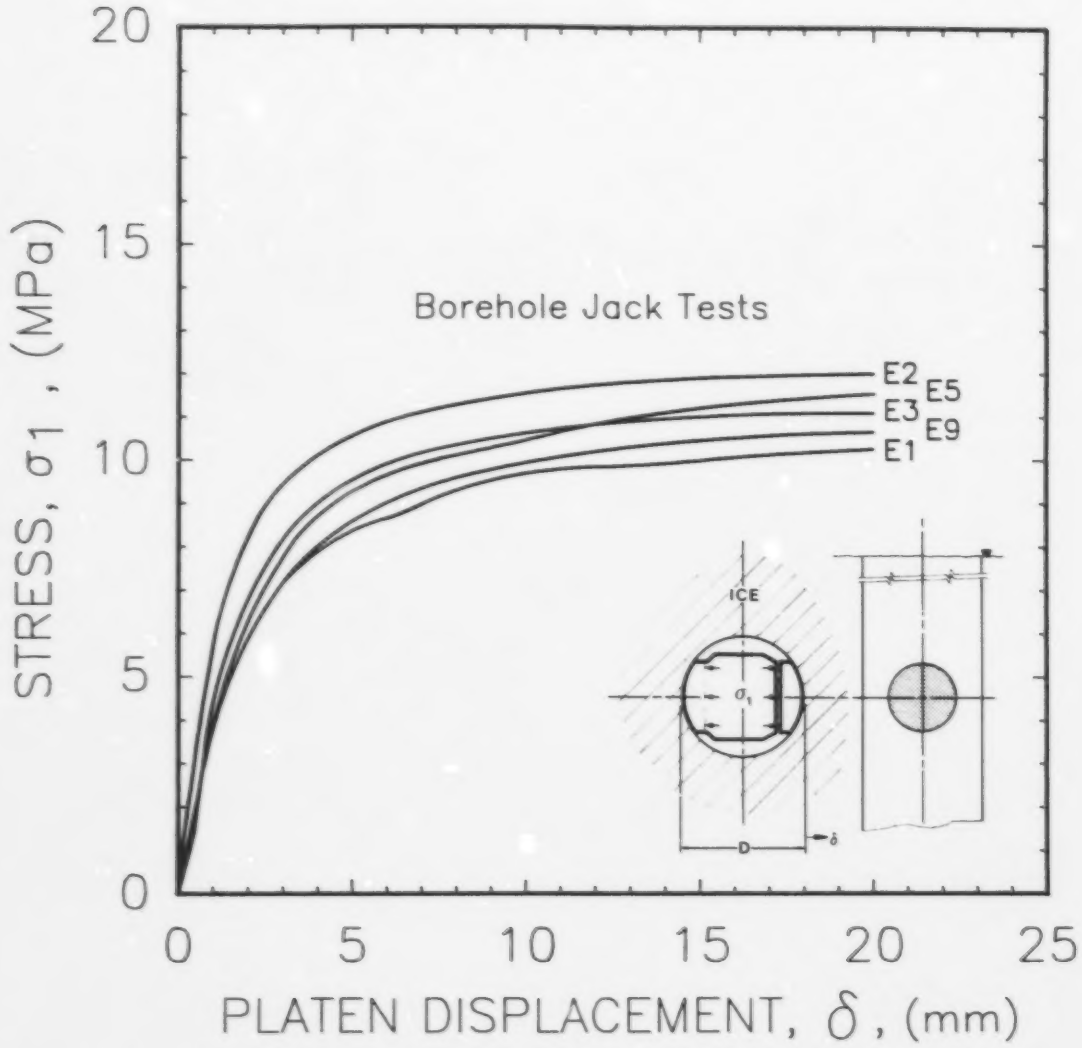

Fig.8. Typical applied stress-platen displacement curves for test series (E) conducted April 26.

assumed to be representative of strength. Secondly, the loading history for each test was examined and the applied stress (σ_{1m}) attained at the point where the displacement rate ($\dot{\delta}$) becomes a maximum ($\dot{\delta}_m$), was used. In conditions of cold ice (i.e. <0°C), σ_{1m} and σ_{1u} are usually concomitant (e.g. Sinha 1986). As will be described later, however, this was found not to be the case for decaying isothermal 0°C ice. Figs 9 and 10 illustrate the criteria as applied to tests conducted on April 12 and April 26 respectively.

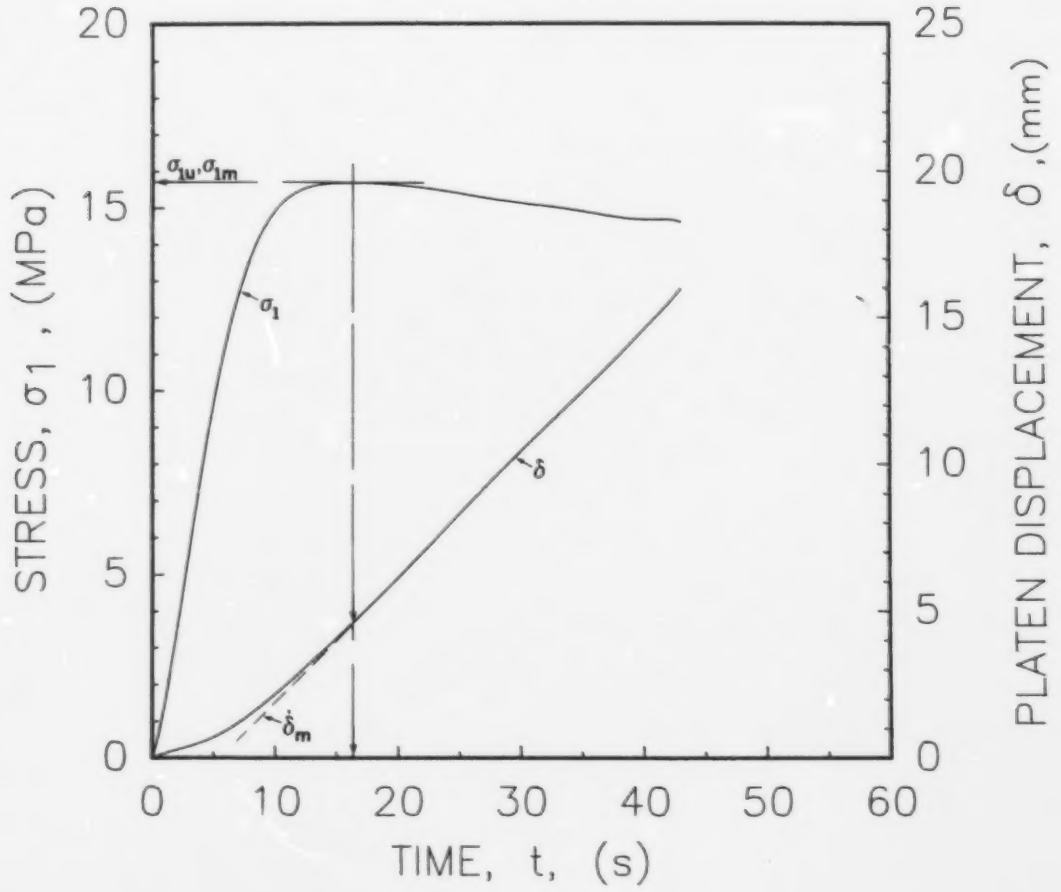

Fig.9. Loading history for test (A4)

RESULTS AND DISCUSSION

The daily mean and range of σ_{1u} and σ_{1m} values obtained over the study period are shown in Fig.11. A reference strength value of approximately 16.1 MPa for σ_{1u} and σ_{1m} is obtained for April 12 after which both steadily declined over the 18-day period to 8.8 MPa and 3.9 MPa on April 29, respectively. For this latter date, a mean value of 3.4 MPa for σ_{1u} was obtained for the black ice cover. For illustrative purposes, the black-ice value and range is shown slightly offset in Fig.11 although the test was performed on the same date as the final test series for the white-ice cover.

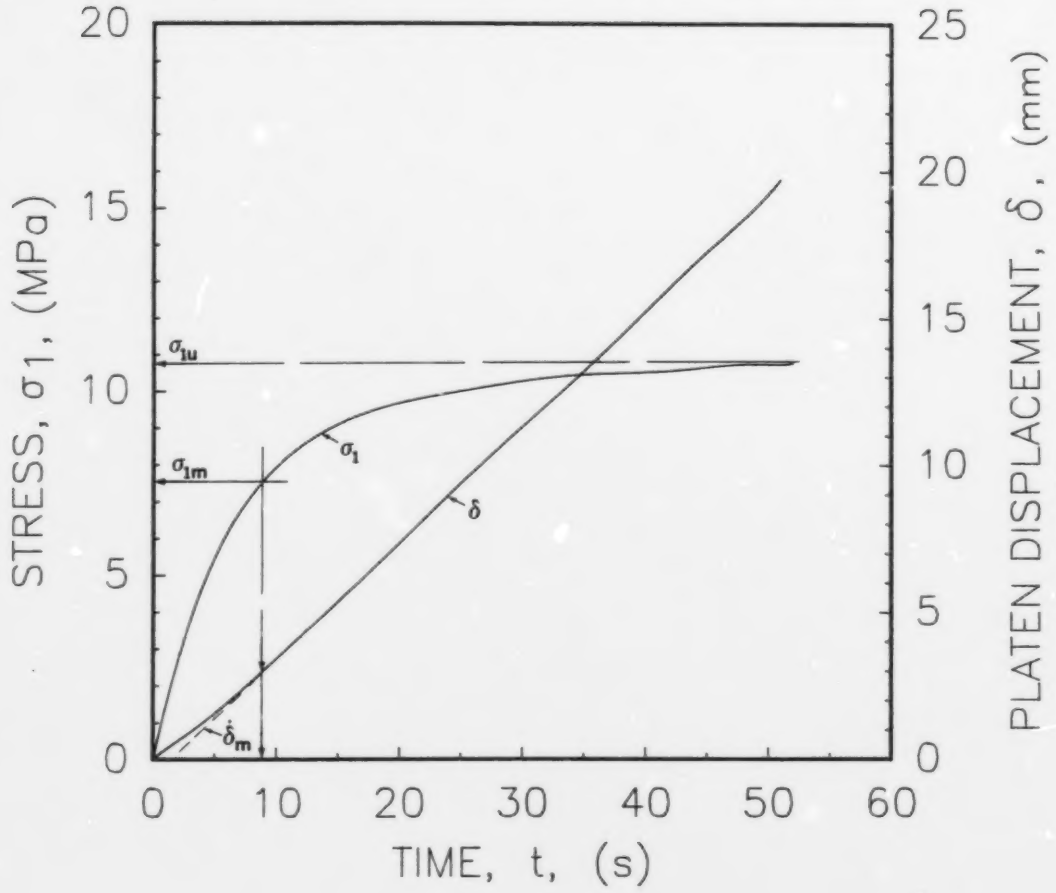

Fig.10. Loading history for test (E8)

The black-ice test series took place at a nearly constant $\dot{\delta}$. The absence of a rise in $\dot{\delta}$ therefore precluded detection of a σ_{1m} value. A constant $\dot{\delta}$ test could be interpreted as representing an approximate compliance minimum for ice when applying this particular borehole jack system. Any strength value which could be defined is probably only indicative of the load required to re-orient and displace the columnar grains within the ice-water matrix. Notably, as the test series progressed, the audible cracking associated with indenture became less apparent and is believed to be indicative of changes in the internal structure of the ice.

One of the more striking features of Fig.11 is the divergence in the σ_{1u} and σ_{1m} values over the study period. As indicated in Fig.10, applied

stress continued to increase well beyond the attainment of σ_{1m} (i.e. at $\dot{\delta}_m$) for tests in more advanced states of decay. The attainment of maximum $\dot{\delta}$ was originally thought to be indicative of the peak strength in confined compression as measured by the borehole jack (not including post peak strength changes). Observations show this to be true for cold ice. The difference in the two strength indices is partly a result of the changing boundary and confining characteristics of the test as the ice became more compliant. Given the difficulties in precisely defining $\dot{\delta}_m$ for some of the later tests (characterized by very gradual rises in $\dot{\delta}$) and the complexities of the response of well-decayed ice to platen indenture, the use of σ_{1u} would seem to allow a more objective definition of a strength value.

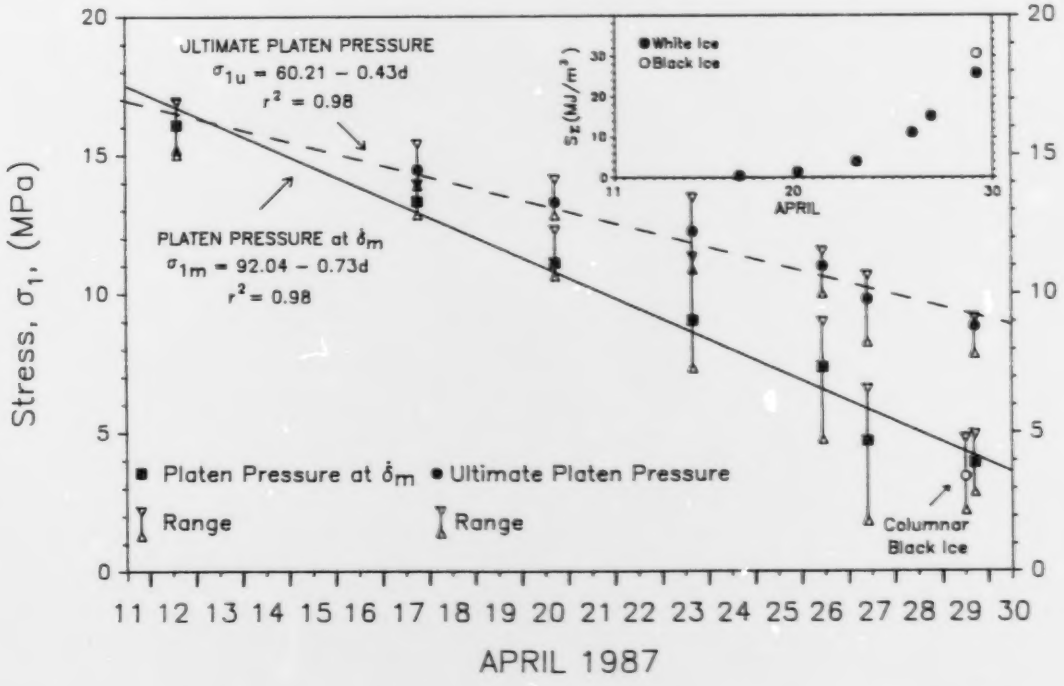

Fig.11. Changes in σ_{1u} and σ_{1m} with time. Inset illustrates the accumulated short-wave radiation over the same period.

Also shown in Fig.11 is the accumulated total short-wave radiation absorbed by the ice sheet (S_Σ, MJ/m^3) for the dates on which ice strength measurements were conducted. As the data suggest, σ_{1u} and σ_{1m} decrease almost linearly with time although S_Σ increases exponentially.

Direct comparison of σ_{1u} and σ_{1m} with S_Σ can be made in Fig.12. Here, strength ratios (strength/original strength) have been plotted against a porosity value to permit comparison with results obtained by others using different strength measurement techniques, such as small-scale beam tests (eg. Shishokin 1965 reported by Bulatov 1970). Porosity (ϕ) is defined as the ratio of liquid water volume to total volume and is simply a linear function of S_Σ:

$$[4] \qquad \phi = S_\Sigma / \rho_i \lambda_i$$

where ρ_i is the density of ice (kg/m^3) and λ_i is the latent heat of fusion for ice (J/kg).

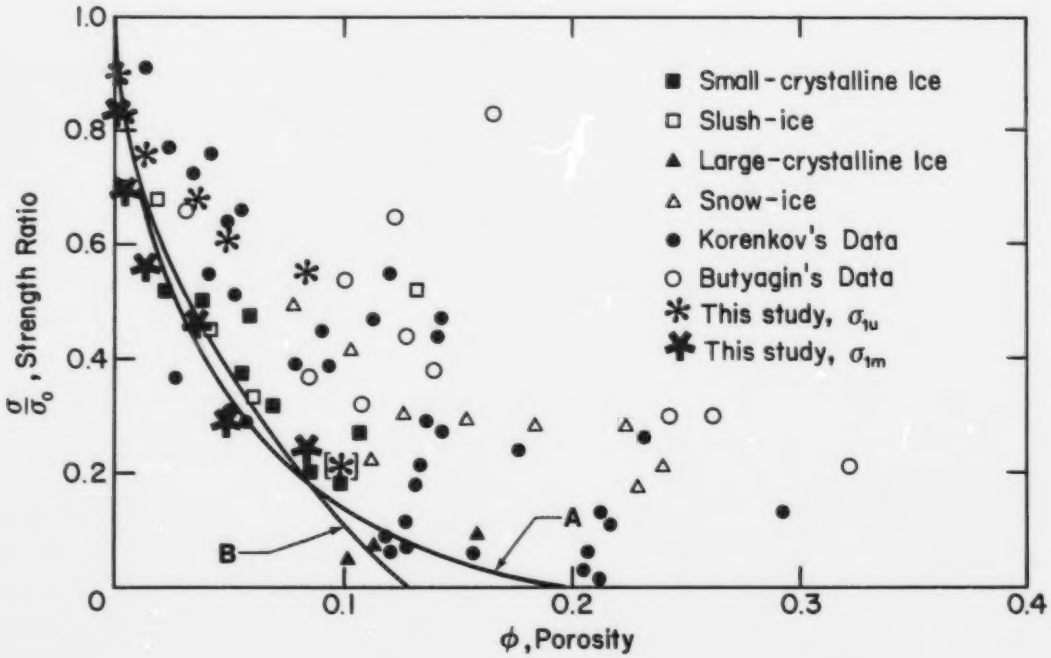

Fig.12. Dimensionless strength versus porosity. Other data adapted from Ashton (1985), originally reported by Bulatov (1970) including the first four legend symbols referring to Shishokin (Bulatov 1970). Curve A is after Bulatov (1970) and curve B after Ashton (1985). Bracketed value refers to black ice.

Fig.12 also depicts two curves representing theoretical models proposed by Bulatov (1970) and Ashton (1985) for the relationship between strength and porosity and data on strength reduction from laboratory and field beam tests reported by Bulatov (1970). Although the models address the mechanism of internal melt in different ways, the resultant curves only differ significantly at high porosity values (ie. $\phi > 0.1$). Moreover, given the scatter of the beam-test data, little verification is offered for either of the models other than to suggest that they simply define a lower bound. Only the data from Shishokin (Bulatov 1970) for small-crystalline ice closely approximates the curves but unfortunately it does not extend beyond the point where the two curves diverge.

The two sets of data obtained in this study track the exponential decrease in the strength-ratio which characterizes the theoretical curves. Moreover, they exemplify the ability of the borehole jack to provide an index of ice strength which for this study decreased during the decay period in a manner supported by other *in situ* tests. In terms of river-ice breakup, the latter points in each data set are the most interesting because they represent conditions only one day before the ice cover was fragmented by upstream forces and driven downstream. At this point, the ice porosity characterizing the white ice zones was 0.083 and for black ice 0.099. Considering that the 1987 breakup could be classified as a thermal event in which upstream forces created by downstream progressing flood waves were near a minimum, these two latter porosity values are believed to be indicative of the near-maximum melt conditions which could prevail prior to the initiation of breakup at the Liard site. Higher values of ϕ might characterize thermal breakup events on river sections of lesser slope or lower velocity than the Liard, but in view of the extremely weakened condition of the black ice on the day preceding breakup, a value of $\phi = 0.1$ is considered to be a near-maximum for pre-breakup river-ice decay. Confirmation of this value from further field tests could permit its use in a predictive mode for forecasting the onset of breakup.

CONCLUSIONS

A first application of the borehole jack for evaluating the deterioration of floating covers which have attained a 0°C isothermal state has been presented. Despite the complexities associated with jack behaviour and the difficulties in defining strength in a strict material properties sense, it has been shown that the device provides a reasonable measure of the decreasing ability of a decaying ice sheet to accept load. Accumulated short-wave radiation, derived from detailed energy balance measurements, is used to predict the resulting melt fraction porosity which is then related to changes in ice-sheet strength measured *in situ*.

An ice-sheet porosity value of 0.1 is considered to be a near-maximum for pre-breakup river-ice decay, although additional field testing is required to confirm this figure. Such a "threshold" value may be useful for predicting both the timing and severity of river-ice breakup.

Future work should concentrate on the mechanisms of short-wave radiation attenuation and the possible consequences of spectral selectivity in the intergranular melt process. Other ice-strength testing techniques, which emulate the dominant modes of failure during breakup initiation (i.e. the determination of crushing and flexural strength) should also be evaluated. *In situ* testing, although difficult, is considered a prerequisite in conditions of advanced decay. To date, little data exists, whether it be field or laboratory generated, on the mechanical properties of ice at 0°C. Expanded knowledge in this area will lead to a better ability to analyse and interpret *in situ* mechanical test results for decaying ice.

ACKNOWLEDGEMENTS

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